TOP QUARK POLARIZATION AND THE SEARCH FOR NEW PHYSICS [a]

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Forward-backward asymmetries A_{FB}^t and A_{FB}^ℓ are observed in the top quark t rapidity distribution and in the rapidity distribution of charged leptons ℓ from top quark decay at the Tevatron proton-antiproton collider, and a charge asymmetry A_C is seen in proton-proton collisions at the Large Hadron Collider (LHC). In this presentation, I summarize research my collaborators and I have done on the interpretation and implications of the Tevatron asymmetries and provide expectations for A_C at the LHC. The two asymmetries A_{FB}^t and A_{FB}^ℓ are connected through the $(V - A)$ spin correlation between the charged lepton and the top quark with different polarization states. The ratio of the two asymmetries provides independent insight into the physics interpretation of the top quark asymmetry. A new physics model which produces more right-handed than left-handed top quarks appears to be indicated by the present Tevatron data, but an improvement in precision is desirable.

1 Introduction

The large mass of the top quark, of order the electroweak scale, suggests that the top quark may be sensitive to electroweak symmetry breaking and to physics beyond-the-standard model. Experimentally, the observation of a larger than expected forward-backward asymmetry A_{FB}^t in the rapidity of top quarks produced at the Fermilab Tevatron collider [1,2] continues to hold considerable attention. The asymmetry is defined as

$$A_{FB}^t = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}, \tag{1}$$

where $\Delta y = y_t - y_{\bar{t}}$ is the difference between the rapidities of the top quark and the anti-top quark, and $N(\Delta y > 0)$ ($N(\Delta y < 0)$) is the number of events with $\Delta y > 0$ ($\Delta y < 0$). The proton beam is chosen as the direction of positive z. In the standard model (SM), the asymmetry is induced by perturbative quantum chromodynamics (QCD) processes beyond the leading order.

The enhanced asymmetry is one of few manifestations of a deviation from predictions of the SM. Many models of new physics (NP) have been proposed to explain the data. A lengthly list of references and a discussion of constraints on these models may be found in Berger *et al.* [3] and in Cvetic *et al.* [4]. Some of the NP models postulate the existence of new states with right-handed couplings of the top quark.

The large mass of the top quark is important in another respect. Its short lifetime means that the top quark decays as a "bare" quark. Its polarization information is retained in the weak decay $t \to b\ell\nu$, passed to its decay products. The lepton ℓ angular distribution in the top quark rest frame is maximally correlated with the top quark spin orientation, providing the opportunity

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to test non-standard features of NP models such as right-handed couplings. Another method to measure the polarization is based on the lepton momentum distribution[5] and is valuable for use with complex final states in which the top quark rest frame is hard to determine. Of particular interest to us have been the implications of models of new physics for the polarization of the top quark, and methods that can be used to measure the polarization[5]. In the SM, strong production of $t\bar{t}$ pairs in quantum chromodynamics (QCD) yields an equal number of positive and negative helicity top quarks, hereafter referred to as t_R and t_L. Electroweak production in single top quark production, for example, yields primarily t_L. Therefore, a demonstration that a significant fraction of top quarks are produced with positive helicity would herald new physics.

In addition to A^t_{FB} of the top quark, the D0 group reports a positive forward-backward asymmetry of charged leptons from top quark decays. The measurement is done in two ways[2,6], both based on data corresponding to an integrated luminosity of 5.4 fb^{-1}. The value $A^\ell_{FB} = (15.2 \pm 4.0)\%$ is measured in the ℓ+jets final states[2]. The second method uses the dilepton final states from $t\bar{t}$ production, where the W bosons from the t and $\bar{t}$ decays both decay leptonically, and the result obtained is $A^\ell_{FB} = (5.8 \pm 5.1(\text{stat}) \pm 1.3(\text{syst}))\%$. A combination of the two measurements yields $A^\ell_{FB} = 11.8 \pm 3.2\%$. The combined result may be compared with the values $(2.1 \pm 0.1)\%$ from simulations of the SM or $(4.7 \pm 0.1)\%$ once QCD+EW corrections are included[7,6], an excess at the level of 2.2 standard deviations. The fact that A^ℓ_{FB} and A^t_{FB} are larger than the SM predictions indicates that the charged lepton strongly prefers to move in the same direction as the top quark from which it originates. Data on the ratio of the two asymmetries tend to favor models in which more t_R than t_L are produced[3], but confirmation with greater statistical and systematic precision is desirable.

In Sec. 2 the asymmetries measured at the Tevatron are defined and our fits in the framework of Z', W', and axigluon new physics models are discussed. The LHC proton-proton collider offers no preferred direction for the measurement a rapidity asymmetry. Nevertheless, charge asymmetries A^t_C for top quarks and A^ℓ_C for leptons can be defined and computed. Using data from the Tevatron, we may obtain expectations for these charge asymmetries, and we compare these expectations with LHC data in Sec. 3. Despite limited statistics, the LHC data on the charge asymmetry are also consistent with a deviation from the SM, although perhaps not as great a deviation as expected from an extrapolation of the Tevatron observations.

The relationship of A^t_{FB} and A^ℓ_{FB} is addressed in Sec. 4. The essential starting point is the $V - A$ structure of the matrix element for the decay $t \to W^+ b \to b\ell^+\nu$. We pay particular attention to the positive/negative helicity state of the top quark because the final momentum and angular distributions of leptons in the laboratory frame depend significantly on the top quark's polarization state. We derive the relationship of the lepton asymmetry A^ℓ_{FB} and the top quark asymmetry A^t_{FB} separately for the left- and right-handed polarization states of the top quark. Different models of new physics produce top quarks with different proportions of left- and right-handed polarization. For example, W' models produce predominantly right-handed top quarks, whereas the axigluon model generates unpolarized top quarks. We use an axigluon model and a W' model in Sec. 4 to illustrate their different expectations for the ratio of the lepton and top quark asymmetries.

2 Tevatron Data and Interpretations

In Berger *et al.*[3], we present fits for three models: flavor-changing Z' exchange, flavor-changing W' exchange, and axigluon models. The minimal version of the Z' model implies a large rate for same-sign top quark pair production at the LHC, not supported by data[9,10,11]. The W' model is constrained by data on the $t\bar{t}$ plus jets final state at the LHC[13,14,12]. The absence of pronounced deviations from the SM expectation in the measured $m_{t\bar{t}}$ invariant mass distribution indicates to us that the axigluon should be heavy and/or broad. Another possibility would be

to place it below $m_{t\bar{t}}$ threshold [15].

We fit data at the Tevatron to determine the parameters of the three new physics models. under consideration. We scan the parameter space of the models requiring that the predictions fit the total cross section as well as CDF data on A_{FB}^t for both $m_{t\bar{t}} <$ 450 GeV and $m_{t\bar{t}} \geq$ 450 GeV within 2σ accuracy.
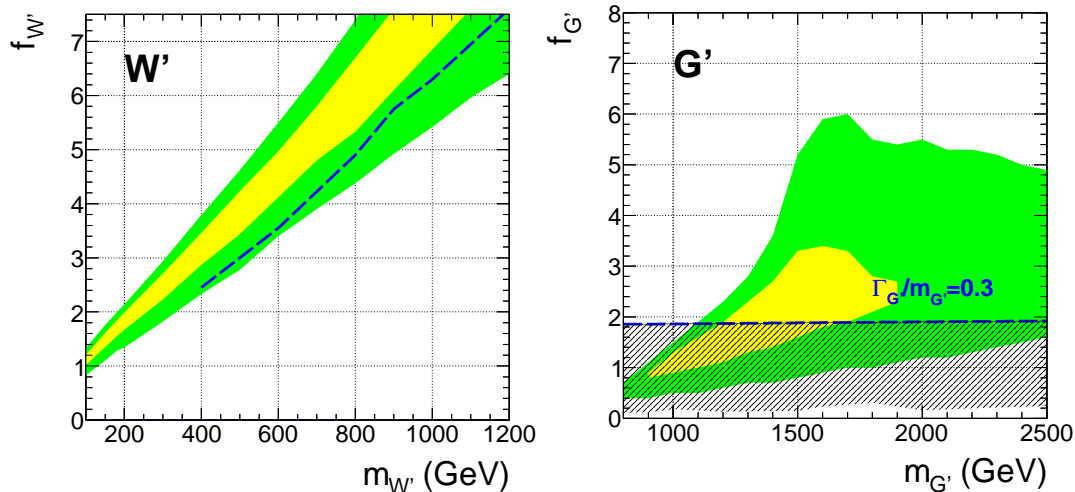

Figure 1: The parameter space of two new physics models determined from fits to the Tevatron $t\bar{t}$ total cross section and A_{FB}^t measured by the CDF collaboration in the intervals $m_{t\bar{t}} <$ 450 GeV and $m_{t\bar{t}} \geq$ 450 GeV. The yellow region fits the data within 1σ and the green region fits within 2σ: flavor-changing W' model, and axigluon model. The dashed line in the W' case shows the bound on the coupling $f_{W'}$ obtained from an analysis of the CMS data on top-pair-plus-one-jet events at the LHC. The blue shaded region in the axigluon case is inferred from the limits set by ATLAS on axigluons from the search for enhancements in the dijet mass distribution.

Figure 1 shows the results of our fits for two of the models. The fit for the Z' model may be found in Berger *et al.*[3]. There is a large region of parameter space in which the W' model can fit the Tevatron data within 1σ and 2σ. However, the region above the blue dashed curve is not allowed since too many $t\bar{t} + j$ events would be produced. In the axigluon case, to achieve good agreement with data at the 1σ level, the mass of axigluon is required to be in the range of about 900 GeV to 1900 GeV. For other axigluon masses, the model can only fit data at the 2σ level. Also shown are some bounds on axigluon masses and couplings obtained from a search for resonances in the dijet invariant mass distribution [16,3].

3   LHC Data and Expectations

The LHC proton-proton collider is symmetric in rapidity, and it is ambiguous to define a forward or backward region. However, the u and d parton densities carry, on average, a larger fraction of the momentum of the proton than the u and d antiquark densities. With the knowledge that there is a forward-backward asymmetry in the perturbative production process for $\bar{q}q \to t\bar{t}$ production, we expect that the top quark at the LHC will be boosted in the direction of the incident quark. As a result, top quarks should accumulate in the region of large rapidity and anti-top quarks will be preferentially in the central region. An asymmetry A_C may be defined at the LHC as

$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)}. \tag{2}$$

Measurements of A_C at the LHC have been published by the CMS and ATLAS collaborations based on data sets with 4.7 fb^{-1} of integrated luminosity [17,18]. The ATLAS central value is an

order of magnitude larger than the CMS value, but they agree within the large uncertainties in both experiments, and they are consistent with the SM prediction.

At the Tevatron, $t\bar{t}$ production is driven by the quark-antiquark initial state parton densities, whereas at the LHC, it is dominated by the gluon-gluon initial state which provides no asymmetry. The overall asymmetry A_C is therefore expected to be diluted substantially at the LHC. An approximate estimate for the LHC asymmetry may be obtained by an extrapolation from the Tevatron result:

$$A_C \quad \approx \quad \frac{\sigma(q\bar{q} \to t\bar{t})}{\sigma(gg \to t\bar{t}) + \sigma(q\bar{q} \to t\bar{t})} \times A_{FB}^t(q\bar{q} \to t\bar{t}) \times \tilde{\epsilon}. \tag{3}$$

The first term represents the fraction of the top-quark pair production cross section induced by the $q\bar{q}$ initial state which is about 17 % in the SM at the LHC at 7 TeV. The second term is the asymmetry induced by the $q\bar{q}$ initial state. Given that about 88% of the $t\bar{t}$ production cross section in the SM comes from the $q\bar{q}$ initial state at the Tevatron, $A_{FB}^t(q\bar{q} \to t\bar{t})$ can be extracted from the top quark forward-backward asymmetry observed at the Tevatron; we use $A_{FB}^t(q\bar{q} \to t\bar{t}) \approx A_{FB}^t/88\%$, where A_{FB}^t is the measured top quark asymmetry. The last term $\tilde{\epsilon}$ in Eq. (3) represents the probability of correct identification of the forward direction, namely how frequently the forward direction represents the direction of the initial state quark. This probability is evaluated in Berger *et al.*[3] for both the Tevatron and the LHC.

Combining all terms, we expect that $A_C \simeq 0.17 \times A_{FB}^t/88\% \times 54\% \simeq 0.1 A_{FB}^t$, where A_{FB}^t is the value measured at the Tevatron. With $A_{FB}^t \sim 20\%$, an extrapolation from the Tevatron provides a model independent estimate for the LHC of $A_C^t \simeq 0.02$, in reasonable agreement with the central value of the ATLAS measurement but in excess of the central value of the CMS measurement. Setting aside for the moment the still large uncertainties of the LHC data, the agreement of the ATLAS measurement with our extrapolation lends credence to the suggestion that new physics contributions are playing a role in the asymmetry measured at the Tevatron. On the other hand, there is evident tension between the Tevatron asymmetry and the central value of the CMS measurement.
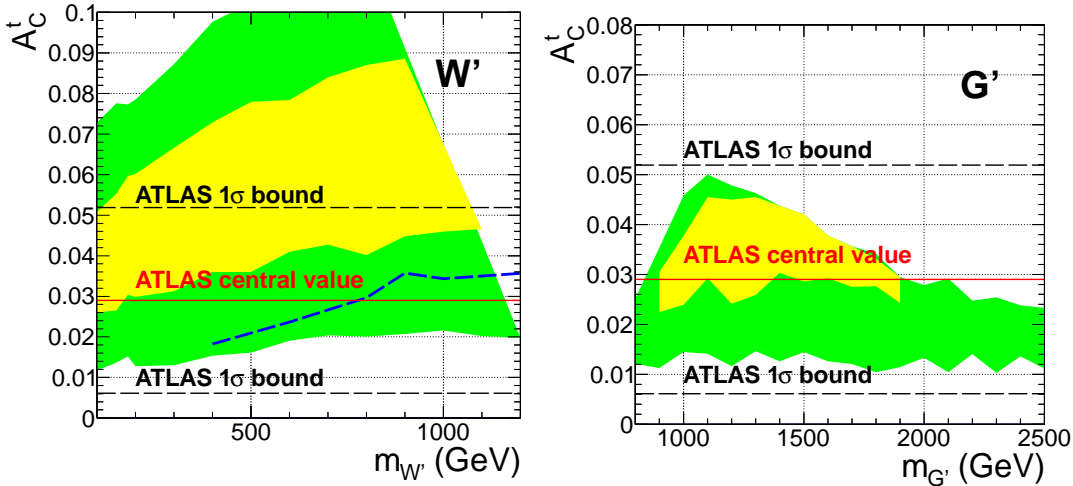

Figure 2: The predicted top quark charge asymmetry, A_C^t, at the LHC at 7 TeV from the W' (left) and axigluon (right) models, compared with the ATLAS results. The yellow and green regions are for the couplings that fit the Tevatron $t\bar{t}$ total cross section and A_{FB}^t within 1σ and 2σ, respectively. The central value measured by ATLAS is marked with the red horizontal line, and the two black dashed lines show the 1σ uncertainty of the measurement. The blue dashed line on the W' figure shows the bound obtained from the analysis of top-pair-plus-one-jet events. The region above this dashed line is disfavored.

The extrapolation from the Tevatron is admittedly rough as it ignores possibly subtle energy-

dependent effects and cancellations between SM and new physics contributions. Turning next to the explicit new physics models discussed in the previous section, we use the allowed parameters for the flavor-changing W' and axigluon models shown in Fig. 1 and calculate A_C at the LHC. The results are shown in Fig. 2, along with a comparison to the ATLAS data. To obtain the ATLAS predictions we use $A_C = 0.006$ for the SM prediction, as done by ATLAS. For the CMS comparison, we use the SM value $A_C = 0.0115$ adopted by CMS. The CMS comparison may be found in Berger *et al.*[3].

Most of the values of A_C predicted in the W' model are larger than the ATLAS central value, but they are within the 1σ uncertainty band. For the axigluon model, all of the predictions of A_C agree with the ATLAS result within the 1σ level. In the axigluon model A_C does not simply increase with the axigluon coupling to SM particles. For $m_{G'} = 1500$ GeV, A_C reaches its maximum at about 4.2%, with coupling $f_{G'} = 2.7$. Therefore, the upper boundary of the yellow region (couplings that fit Tevatron data within 1σ) overlaps the green region (couplings that fit Tevatron data within 2σ) for some $m_{G'}$. The G' model predicts smaller values of A_C than the W' model because there is a change of the sign of the s-channel propagator. When the invariant mass of the $t\bar{t}$ system is larger than the mass of the axigluon, the contribution to A_C from the interference term is negative. When comparing with the CMS data, we find in Berger *et al.*[3] that the predicted values of A_C are outside of the 1σ band. Unless the central value increases in updated measurements, the CMS data disagree with the simplest new physics models based on W' or axigluon contributions.

4 The relationship of A_{FB}^t and A_{FB}^ℓ

The top quark is the only quark that decays quickly, before hadronization takes place, and its polarization determines the kinematic distribution of its final state decay particles. Therefore, it should be possible to understand the relationship of A_{FB}^t and A_{FB}^ℓ based on the kinematics of the charged lepton in the decay of a top quark with different polarization states.

The charged lepton in top quark decay is a powerful analyzer of the polarization of the top quark [19]. Owing to the $V - A$ structure of the charged current in the SM, the angular distribution of a charged lepton ℓ^+ from top quark decay $(t \to W^+(\to \ell^+\nu)b)$ in the top quark rest frame is

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\text{hel}}} = \frac{1 + \lambda_t \cos\theta_{\text{hel}}}{2}, \qquad (4)$$

where λ_t denotes the top quark helicity, and θ_{hel} is the angle of ℓ^+ with respect to the direction of motion of the top quark in the overall center-of-mass system of the $t\bar{t}$ production process. We use the helicity basis in our calculations; $\lambda_t = +$ denotes a right-handed top quark (t_R), and $\lambda_t = -$ a left-handed top quark (t_L). Once the top quark is boosted along its spin direction, the angular distribution of the charged lepton relative to the direction of motion of the top quark deviates from $(1 \pm \cos\theta)$, and it becomes sensitive to the energy of the top quark E_t (or equivalently its velocity β). We derive

$$\frac{d\Gamma}{\Gamma d\cos\theta_{t\ell}} = \frac{1 - \beta\cos\theta_{t\ell} + \lambda_t(\cos\theta_{t\ell} - \beta)}{2\gamma^2(1 - \beta\cos\theta_{t\ell})^3}, \qquad (5)$$

where $\beta = \sqrt{1 - m_t^2/E_t^2}$, $\gamma = E_t/m_t$, and $\theta_{t\ell}$ is the angle between the charged lepton and the direction of motion of its parent top quark.

To obtain the forward-backward asymmetry in the laboratory frame, we must rotate the angular distribution in Eq. 5 from the top quark direction of motion to the laboratory coordinate axes. We use a function $R_F^{\ell, \lambda_t}(\beta, y_t)$ to represent the probability that a lepton with positive charge lands in the forward region when it originates from a top quark with velocity β, rapidity

y_t, and polarization λ_t. Formally,

$$R_F^{\ell,\ \lambda_t}(\beta, y_t) = \frac{N_F^\ell}{N_F^\ell + N_B^\ell}. \tag{6}$$

where N_F^ℓ (N_B^ℓ) denotes the number of leptons ℓ in the forward (backward) region in the laboratory. Moreover,

$$A_{FB}^{\ell,\ \lambda_t}(\beta, y_t) = 2R_F^{\ell,\ \lambda_t}(\beta, y_t) - 1. \tag{7}$$

It is noteworthy that an explicit analytic expression can be obtained in closed form for $R_F^{\ell,\ \lambda_t}(\beta, y_t)$ in the laboratory frame. The derivation is somewhat lengthy, and it is presented in the Appendix of Berger *et al.*[3].

The functions $R_F^{\ell,\ \lambda_t}(\beta, y_t)$ in Eq. 6 and $A_F^{\ell,\ \lambda_t}(\beta, y_t)$ in Eq. 7 are functions of the top quark momentum. To obtain the numbers of leptons in the forward and backward regions, we must convolve $R_F^{\ell,\ \lambda_t}(\beta, y_t)$ with the top quark momentum spectrum, i.e.

$$\frac{N_F^\ell}{N_F^\ell + N_B^\ell} = \frac{1}{\sigma} \sum_{\lambda=+,-} \int R_F^\lambda(\beta, y_t) \frac{d^2\sigma|_{\lambda_t=\lambda}}{d\beta dy_t} d\beta \wedge dy_t, \tag{8}$$

$$\frac{N_B^\ell}{N_F^\ell + N_B^\ell} = \frac{1}{\sigma} \sum_{\lambda=+,-} \int \left[1 - R_F^\lambda(\beta, y_t) \right] \frac{d^2\sigma|_{\lambda_t=\lambda}}{d\beta dy_t} d\beta \wedge dy_t, \tag{9}$$

$$A_{FB}^\ell = \frac{1}{\sigma} \sum_{\lambda=+,-} \int \left[2R_F^\lambda(\beta, y_t) - 1 \right] \frac{d^2\sigma|_{\lambda_t=\lambda}}{d\beta dy_t} d\beta \wedge dy_t \tag{10}$$

where $\dfrac{d^2\sigma|_{\lambda_t=\lambda}}{d\beta dy_t}$ labels the differential $t\bar{t}$ production cross section for a top quark with specific kinematics (β, y_t, λ_t), and σ stands for the $t\bar{t}$ total production cross section.

The observed positive top-quark asymmetry A_{FB}^t indicates that more top quarks are produced in the forward region than in the backward region of rapidity. Both t_R and t_L can generate a positive lepton asymmetry A_{FB}^ℓ from a positive A_{FB}^t. However, a t_L would need a large boost along the proton beam line (i.e. in the large forward rapidity region) to overcome the fact that most of the charged leptons from its decay move against it in its rest frame. A right-handed top quark t_R can yield a positive A_{FB}^ℓ even for top quarks near the $t\bar{t}$ threshold region. Therefore, the large positive top quark and lepton asymmetries A_{FB}^t and A_{FB}^ℓ observed by the D0 collaboration indicate that the top quark polarization and the kinematics of the top quarks, y_t and E_t, may be playing a non-trivial role.

The correlation between the charged lepton asymmetry and the top quark asymmetry is significantly different for different polarization states of the top quark, and it may therefore shed light on the nature of the physics that causes the forward-backward asymmetries at the Tevatron. We choose the W' and axigluon models as two reference models to examine the correlation at the Tevatron and the LHC.

The axigluon and W' models admit good fits to A_{FB}^t at the Tevatron, but they provide distinct predictions for the polarization and kinematics of the final state top quark. The W' model produces dominantly t_R while the axigluon model generates an equal number of t_R and t_L with more energetic top quarks since the quarks come from the decay of a heavy axigluon. In Fig. 3, we show the results of our calculation of the charged lepton asymmetry at the LHC using the parameters determined in our 1σ fits to the $t\bar{t}$ total cross section and the most recent CDF data on A_{FB}^t. Figure 3 shows charged lepton asymmetry for the LHC together with the top quark charge asymmetry A_C^t. The results for the Tevatron are shown in Berger *et al.*[3]. There are vertical red lines in Fig. 3 at $A_C^t \sim 0.03$ to show the central values of the asymmetries measured by ATLAS, and two black dashed lines show the extent of the quoted experimental 1σ
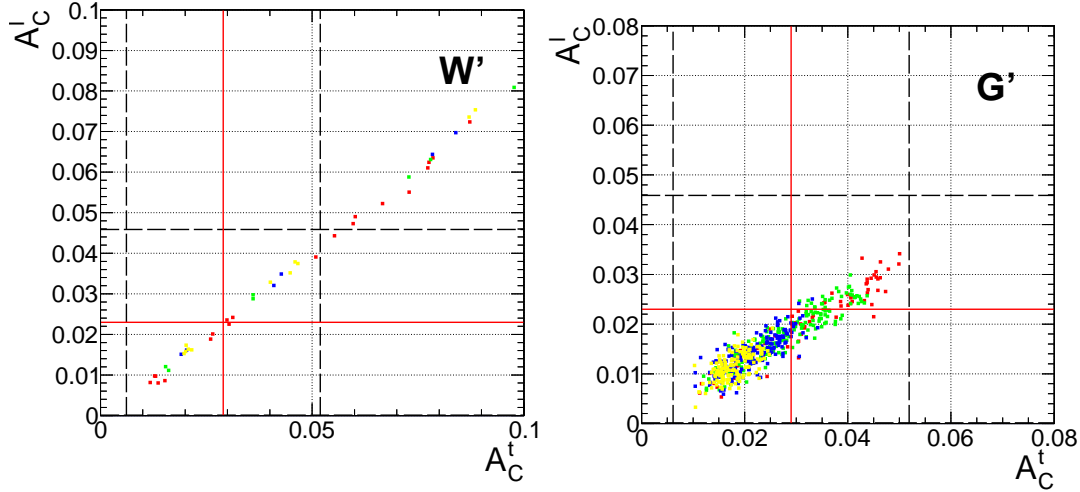
Figure 3: The correlation between A_C^t and A_C^ℓ at the LHC for the W' (left) and axigluon models (right). The vertical (horizontal) red line and the two black dashed lines show the central value of A_C^t (A_C^ℓ) and the 1σ uncertainty bands measured by ATLAS at the LHC. The green (red) dots are obtained from the parameters that fit the Tevatron $t\bar{t}$ cross section and A_{FB}^t within 1σ (2σ).

uncertainty bands. The horizontal red line shows the central value of A_C^ℓ measured by ATLAS, and the horizontal black dashed lines show the 1σ uncertainty values.

The predicted charged lepton asymmetries stretch out over a range of values depending on the values of the axigluon or W' masses used in the fits to the Tevatron data. At the LHC, there are parameters in both models (obtained from the Tevatron fits) that can reproduce the values of A_C^t and A_C^ℓ measured by ATLAS, shown by the fact that the intersection of the vertical and horizontal red lines passes through the scattering of dots. On the other hand, there is a wide range of dots in the W' model that are above the central values of A_C^t and A_C^ℓ, and out of the 1σ uncertainty band. In the axigluon model, all the values of A_C^t and A_C^ℓ are consistent with ATLAS measurements within the 1σ bands. The LHC and Tevatron data together could reduce the allowed parameter spaces of the two models.

The size of the top quark asymmetry, in excess of SM expectations, is one indication that new physics may be playing a role. The charged lepton asymmetry provides a second and independent indication of the presence of new physics since it points to the possibility that more right- than left-handed top quarks are being produced. It is important to confirm the charged lepton asymmetry. This goal could be realized with an analysis of the full data set in D0. It would be valuable also to have a measurement of the charged lepton asymmetry from the CDF collaboration.

Acknowledgments

I am pleased to commend Marc Besancon for his very professional and self-effacing organization of the excellent scientific program of this conference on Beyond the Standard Model of Particle Physics in Quy Nhon, Vietnam in July 2012. I am glad to have had this opportunity to make his acquaintance.

This conference was the most recent in of the "Rencontres du Vietnam" series established by Jean Tran Thanh Van. Van has contributed much over the years to fostering international scien-

tific collaboration, and to facilitating interactions among experimenters and theorists, through his establishment of the ongoing "Rencontres de Moriond" series begun in 1966 and the "Rencontres de Blois" series started in 1989. During this visit to Vietnam, conference participants had the opportunity to learn first-hand of the ambitious International Center for Interdisciplinary Science and Education that he is creating in Quy Nhon, Vietnam and to visit the sea-side construction site. Once operational, the intent is that the Center will host high-level national, regional, and international meetings in basic and applied science, medicine, the humanities, and social sciences.

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